Novel Scanned Beam Millimeter-Wave Antenna Using Micromachined Variable Capacitors on Coplanar Structures

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ABSTRACT: This paper presents a new approach of modelling, design, and characteristics of variable radio frequency micro-electromechanical system (RF-MEMS) capacitor integrated on leaky wave antenna (LWA) operating at 94 GHz. This antenna was implemented on grounded coplanar waveguide (CPW). A 2D distributed mathematical model for the capacitor has been developed along this paper; we formulate and solve the static and dynamic problems associated with the proposed RF-MEMS capacitor. The obtained results are in good agreement with the ANSYS simulations. A full-wave simulation was used to investigate the microwave performances of the proposed antenna. This prototype exhibits continuous tuning radiation angle and beamwidth capability by tuning bias voltages from 0 V to 60 V. The proposed antenna presents flexibility, high directivity, compact size, and low-cost characteristics. The LWA can be used in applications which require high-performance such as imaging arrays and collision-avoidance radars.

Categories and Subject Descriptors
C.2.1 [Network Architecture and Design] Wireless communication; B.1.4 [Microprogram Design Aids]

General Terms: Antenna, Radio frequency micromechanical system, Image arrays

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1. Introduction

Over the last decade, RF-MEMS research has been strongly concentrated on developing robust, reliable MEMS switches with shunt capacitance and phase shifters for cell phone, filters, and wideband radar applications [1][7]. This paper focuses on the modeling, design and implementation of tunable serial RF-MEMS capacitor on coplanar waveguide (CPW) with very low insertion loss from 85 to 105 GHz. This capacitor will be integrated in LWA to obtain a scanning-beam from broadside to endfire direction. This capacitor can be easily built using surface micromachining in CPW center microstrip conductor by having two plates facing each other separated by an air-gap. Recently, much work has concentrated on the development of scanning-beam antennas based on simple microstrip metamaterials structures [8], [9] and MEMS technology [10], [11] due to their high quality factor Q.

The design of LWA with variable serial capacitance obtained with RF-MEMS technology creates a variation of the propagation constant (β) permitting the scanning-beam of the antenna from the broadside to close endfire direction. To understand the exact mechanisms, a multiphysics model that captures the coupling among electromagnetic and mechanical domains is required. An electrostatic force caused by the DC bias voltage (V_{DC}) is then translated into motion. This motion ends when electrostatic force and mechanical force are equal. In this effort, many techniques have been published to push the tuning range of MEMS variable capacitors [1], [3], [7]. A variation of the propagation constant caused by the motion of the capacitor movable plate permits the variation of the antenna beam direction. In this work, we will propose a new LWA with a regularly number of RF-MEMS serial capacitors (N=10) which is fabricated by surface micromachining technology, for millimeter-waves range. The dimensions of this capacitor are fully compatible with PolyMUMPS process. Sophisticated and accurate full-wave analyses such as Method of Moment (MoM) and Differential Quadratic Method (DQM) are given for analyzing, in general, any particular geometry instance of the antenna under consideration.

This paper is structured as follows: In Section II, the topology and concept of the proposed MEMS capacitor in CPW structure is presented. Section III shows the theory of how MEMS capacitors move. Section IV, presents the fabrication process of unit cell of the antenna with MEMS capacitors followed by sections V, presenting simulations results of this antenna.

2. Antenna Unit-Cell Design

2.1 Topology of RF-MEMES capacitor and principle

Most RF-MEMS devices are actuated using electrostatic forces. Among the most commonly used types of actuators are the parallel or lateral plate actuators. Nevertheless, electrostatic actuation has some limitations due to its nonlinear nature. This section presents a novel control design that regulates the response of a unit cell (UC) of the CPW with serial MEMS capacitor that schematically illustrated in the Fig. 1a.

The RF-MEMS capacitor consists of a metal movable plate, suspended on the gap of CPW center strip conductor. This movable plate is supported at either ends by metal (anchors, Fig. 1(b) attached to the center conductor. The capacitor fixed plate is connected to the bottom ground plane through simple microstrip as shown in Fig. 1(b-c). Since the top plate is free to move, the serial capacitance can be increased by decreasing the distance of separation. This is done by applying a V_{DC} voltage between the top and the bottom capacitor plates as shown in Fig. 2. This V_{DC} voltage difference sets up an electrostatic force of attraction and pulls the movable plate toward the fixed plate, thereby decreasing the distance of separation.
and increasing the capacitance. The pull-in voltage can be calculated from the effective spring constant of the support of the movable plate, as is found to be [1]:

\[ V_{\text{pull-in}} = \frac{8k_d d^3}{27A e_0} \]  

(1)

Where \( k_d \) is the effective spring constant, \( d \) is the rest gap between the movable plate and the signal line and \( A \) is the area of the movable plate.

2.2 Problem Formulation of MEMS Capacitor

In previous works researchers used 1D lumped model to derive MEMS capacitor equations [1], [12]. In this present work we used a 2D distributed model in this approach the electrostatic force is a function of deflection unlike in 1D model the electrostatic force is uniformly distributed on the area. Hence the 2D distributed model can attain more accurate solutions [12]. The MEMS capacitor is modeled using Euler-Bernoulli beam theory. It's given by the following nondimensional coupled integral-partial differential equation and its associated boundary conditions. Details of the calculations are presented in [13].

\[ \ddot{w} + c \dot{w} + \int_0^1 \left( w(x, t) \right)^2 dx = \alpha_1 \left( \frac{d^2}{d t^2} \right)^2 + \alpha_2 \frac{V_{DC}^2}{(1 - w)^2} \]  

(2)

\[ w(0, t) = w(1, t), \quad w'(0, t) = w'(1, t) = 0 \]

where \( w(x, t) \) is the deflection of each microbeam at time \( t \) and at locations \( x \). the dot denote the derivative with respect to time \( t \) and the prime derivatives with respect to the spatial variable \( x \). \( w \) is the nondimensional natural frequency, \( V_{DC} \) is DC voltage and \( L \) is the length of capacitor movable plate. The variables nondimensionalized using the following form

\[ w = \frac{\ddot{w}}{d}, \quad x = \frac{x}{L}, \quad t = \frac{t}{\tau}, \quad \tau = \sqrt{\frac{12d^2}{E_{ij} b h^3}} \]

where the hats denote the corresponding dimensional quantities, \( r \) is the density, \( E \) is the modulus of elasticity, \( d \) is the initial air-gap distance between both capacitor plates. \( b, h, A = bh \) and \( I = \frac{bh^3}{12} \) are movable-plate width, thickness cross-section area and second moment of area, respectively.

According to previously published works [13], the Differential Quadrature Method DQM is a suitable method to produce a reduced-order model (ROM) in the case of clamped-clamped microbeam (plate) with nonlinear electrostatic force. We use \( n \) grid points to discretize the space and obtained a ROM given by three ordinary differential equations (ODEs), describing the motion of the MEMS capacitor. The geometric and physical parameters of the MEMS capacitor are given in Table 1.

<table>
<thead>
<tr>
<th>( L ) (μm)</th>
<th>( W ) (μm)</th>
<th>( H ) (μm)</th>
<th>( D ) (μm)</th>
<th>( P ) (Kg/m³)</th>
<th>( E ) (GPa)</th>
<th>( E ) (F/m)</th>
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</thead>
<tbody>
<tr>
<td>494</td>
<td>165</td>
<td>1.5</td>
<td>4.75</td>
<td>2300</td>
<td>166</td>
<td>8.85</td>
</tr>
</tbody>
</table>

Table 1. Geometric and physical parameters of the MEMS capacitor

2.3 Mechanical Performances of MEMS Capacitor: Static Analysis and Stability Studies

The static problem can be formulated by setting the time derivatives terms in equations (2) to zero. Then we discretize the space using DQM and we solve the obtained system of equations. The capacitor beam deflection under an applied DC voltage. We examine these deflections by developing closed-form solutions, from which the maximum deflection and associated voltage are determined. Fig. 3 shows the variation of the static deflections at the center of the beam with the applied DC voltage. For a given DC voltage the beam has two equilibrium solutions: one is stable (lower branch) and the other is unstable (upper branch). As the voltage is increased, these solutions meet at the pull-in point, which is characterized by the pull-in voltage 60.6V and maximum deflection of 2.87μm. Hence the static analysis shows that MEMS devices should be designed to operate below these values to ensure the stability.

It can be seen in Fig. 3 that only discretizing the space into 9 grid points (n = 9) gives improved results compared to those given under Analysis Systems ANSYS simulator.

For 1D model approach the pull-in occurs when center deflection reaches 33% of the air gap d [14] - [15]. Whereas in our 2D distributed model pull-in occurs when center deflection reaches 60.5% of the air gap d as shown in Fig. 3.

To study the global stability of the limit-cycle solutions obtained by solving equation (2), we investigate the motion of the MEMS capacitor for a set of initial conditions in the proximity of either the stable or unstable fixed points. In fact, we use Long Time integration LTI [16] to determine the stability of the MEMS capacitor by assuming a set of initial conditions belonging to the
phase space of the system. To determine these initial conditions, associated with the system, we divide the phase plane using a grid composed of 500×500 lines [16]. The grid points are chosen as initial conditions to solve equation (2).

In Figure 4, we show the basin of attraction of bordered solutions of the MEMS capacitor for damping $c = 0.0008$ and $V_{DC} = 60$ V. The white regions correspond to limit of initial conditions that leads to pull-in. These regions correspond to the case in which the pull-in fails to set the capacitor to its down state. Outside the region, pull-in occurs; the color levels indicate the magnitude of the pull-in time. More contrasted colors correspond to smaller pull-in times. We note that the choice of the initial conditions is crucial for determining the stable region of the MEMS capacitor.

Fig. 5 shows the Up/Down state of the capacitor movable plate with a 0.6 μm thick aluminum membrane and 10 μm air-gap. The holes in the membrane are 4 μm in diameter, where their effects on the up-state capacitance are negligible if the diameter of the holes is less than $3–4d_0$, and the electrostatic force is not affected by the hole density. Therefore, on the other hand, the holes do affect the down-state capacitance and result in a reduced capacitance ratio. The high stress regions are located in ends and central capacitor movable plate. These are confirmed using 3-D electrostatic simulations.

2.4 Electromagnetic Performances of the antenna unit cell

Figure 6 shows an electromagnetic model of the unit cell of the antenna with serial RF-MEMS capacitor. The dimensions of the CPWG line are illustrated in table 1. The capacitors $C_1$ and $C_2$ are produced by the discontinuities at the ends of the capacitor fixed plate. $C_3$ represents the RF-MEMS capacitor. The resistance $R$ and $L$ indicate the model of the strip-conductor between the capacitor fixed plate and the ground plane (GND) of the CPW.

The circuit model parameters are optimized to fit the S-parameters obtained from the full wave electromagnetic simulation, using ADS-MOMENTUM 2008 as shown in Fig. 7. Close to 94 GHz, the equivalent capacitance in the circuit model is 97 fF and 72 fF for up-state and down-state respectively. At operating frequency, we can see also that the return loss $S_{11}$ and the insertion loss $S_{21}$ are equal to 36 dB and 2 dB respectively.

3. Proposed Antenna and Results

The proposed new LWA is capable of continuous scanning-beam by tuning bias voltage $V_{DC}$ of the RF-MEMS capacitors along the antenna. The scanning is produced from the
broadside direction to close the endfire direction. In addition to its scanning capability, the antenna provides beamwidth control functionality. In addition, LWA support a fast wave on the guiding structure, where the phase constant $\beta$ is less than the free-space wave number $k_0$. The leaky wave is therefore fundamentally a radiating type of wave, which radiates or leaks power continuously as it propagates on the guiding structure. The operation is therefore quite different from a slow-wave or surface-wave type of antenna, where radiation mainly takes place at each discontinuity formed by RF-MEMS serial capacitors along the CPW center conductor, and at the end of the LWA [17]. The propagation wave number $k_c = \beta - j\alpha$ on the guiding structure is complex, consisting of both a phase constant $\beta$ and an attenuation constant $\alpha$ along the antenna. More addition, most of leakage power is radiation in the beginning of structure and exponentially decreases to ward the end as indicated by Fig. 8.

The complete antenna with a closed package is shown in Fig. 9. The fabrication technics are fully compatible with PolyMUMPS process. Sophisticated and accurate full-wave analyses such as Method of Moment (MoM) and Differential Quadratic Method (DQM) are given for analyzing. The proposed antenna has been engineered and has demonstrated the very electromagnetic performances and potentialities of this concept.

4. Conclusion

In this paper a novel concept of scanning-beam antenna for radar applications is presented. Using voltage-controlled tuning elements $V_{DC}$, a LWA has a narrow scanning range near the endfire direction at 94 GHz. This scanning was possible from 0° to +20° high directivity reconfiguration. The resonant frequency of the LWA has been controllable between 85 GHz and 105 GHz, for a capacitor movable-plate deflection from 0 µm to 3.3 µm. The fabrication technics are fully compatible with PolyMUMPS process. Sophisticated and accurate full-wave analyses such as Method of Moment (MoM) and Differential Quadratic Method (DQM) are given for analyzing. The proposed antenna has been engineered and has demonstrated the very electromagnetic performances and potentialities of this concept.

References


